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Review of NO_x reduction technologies in CI engines fuelled with oxygenated biomass fuels

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ABSTRACT

Oxygenated fuels like biodiesel and alcohols have the potential to provide a reliable and a cost effective alternative to India's increasing future energy demands. They have a prospective future since they are renewable and can be produced easily in India's rural areas. Due to rapid industrialization and the increased number of vehicles on the road, the energy needs of the country are increasing rapidly. Oxygenated fuels can substantially replace the large demand for diesel to generate power for the industries and to fuel diesel engines of the vehicles. In spite of the many advantages of using them, most of the researchers have reported higher NO_x emissions, which is a deterrent to the market expansion of these fuels. The present program aims to review the NO_x emissions from the CI engines fuelled with oxygenated fuels. To meet the stringent emission norms, the various NO_x reduction technologies like use of additives, retarded fuel injection timing, biodiesel emulsion with water, and exhaust gas recirculation are reviewed. The results of the most effective and low cost technique of EGR in DI diesel engine fuelled with biodiesel–diesel blends and tri-compound oxygenated diesel fuel blends (ethanol–biodiesel–diesel fuel blends and methanol–biodiesel–diesel fuel blends) are presented.

Contents

Abbreviations: BSEC, brake specific energy consumption; bTDC, before Top Dead Center; BMEP, brake mean effective pressure; BTE, brake thermal efficiency; CA, crank angle; CO, carbon monoxide; CO_2, carbon dioxide; CHR, cumulative heat release; CI, compression ignition; DI, direct injection; EGR, exhaust gas recirculation; EHN, ethyl hexyl nitrate; THC, total hydro carbon; JME, jatropha methyl ester; NO_x, oxides of nitrogen (NO and NO_2); ppm, parts per million; PM, particulate matter; RME, rapeseed methyl ester; REE, rapeseed ethyl ester; TDC, Top Dead Center.

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1. Introduction

The legislated maximum levels of emissions from engines have been made more stringent. The test limits of EURO III are about 30–40% lower when compared to that of EURO II for diesel passenger cars and light commercial vehicles and there is a further drop of about 30% for EURO IV. Future regulations like EURO V and presumably VI will force diesel engine manufacturers to drastically reduce NO_x and particulate matter emissions [1]. The increase in prices of diesel fuels, stringent emission regulations and a foreseeable future depletion of petroleum reserves have forced us to look for new technologies to reduce vehicular emissions. Among the various developments to reduce emissions, the use of oxygenated fuels like alcohols, biodiesel and vegetable oils etc., in diesel engines is an effective way to reduce vehicular pollution. Biodiesel and ethanol can be produced from feed stocks that are generally considered to be renewable. Since the carbon in biodiesel originates mostly from CO_2 in the air, the full cycle CO_2 emissions for biodiesel contribute much less to global warming than fossil fuels [2].

2. Indian scenario

Biodiesel and ethanol are the renewable and viable fuel options for automobiles of countries like India with a staggering reliance on imported petroleum fuels. It is only in recent years that systematic efforts have been made to utilize vegetable oils and alcohols as fuels in engines. Many literature reviews [3–7] show that European countries and the USA have mainly concentrated on saffola, rapeseed, linseed, sunflower, peanut, soybean oils, etc., as alternative fuels for diesel engines, which are essentially edible in nature. In the Indian context, only non-edible vegetable oils can be seriously considered as fuel for IC engines as the edible oils are in great demand and are far too expensive at present [8–10]. The enormous potential of biodiesel and alcohols is yet to be realized in India. Concrete plans are being formulated to utilize large tracts of uncultivable wasteland to grow the tree borne oil seeds plantation.

3. Oxygenated fuels

Oxygenated fuels like vegetable oils, biodiesel and alcohols like ethanol and methanol have considerable oxygen content. They can be easily produced from common biomass resources, are environmental friendly, are biodegradable and contribute to sustainability. Producing and using oxygenated fuels for transportation offers an alternative to fossil fuels that can help provide solutions to many environmental problems. Using oxygenated fuels in motor vehicles helps to reduce green house gases (GHG) emissions. Biodiesel and ethanol provide significant reductions in GHG emissions compared to gasoline and diesel fuels. Due to the low content of pollutants such as sulfur in oxygenates, the emissions from them are much lower than that of conventional fuels.

3.1. Biodiesel

The American Society for Testing and Materials (ASTM) defines biodiesel fuel as mono alkyl esters of long-chain fatty acids derived from renewable lipid feed stocks, such as vegetable oils or animal fats, for use in diesel engines [11]. The definition excludes pure vegetable oils and mono- and di-glycerides which cannot be considered as biodiesel. Furthermore, the fact that biodiesel must be produced from renewable fats eliminates any confusion with other substances to which this name has been attributed in the past [12]. Further specification regarding its general use in diesel engines differentiates it from other bio-fuels, such as ethanol or other gasoline substitutes.

3.2. Alcohol

Methanol and ethanol are two accepted alternative fuels which can be produced from biomass sources. Neither of the fuels is well suited for use in diesel engines, and the use of high compression ratios, ignition improvers and ignition assistance devices is common [13]. Methanol can be produced from coal or petrol based fuels with low cost production, but it has a restrictive solubility in diesel fuel. Ethanol is a biomass based renewable fuel, which can be produced by alcoholic fermentation of sugar from vegetable materials. It is a low cost oxygenate with high oxygen content (35%). The use of ethanol in diesel fuel can yield significant reduction of particulate matter emissions for motor vehicles [14].

3.3. Tri-compound fuel blends

Although biodiesel cannot entirely replace petroleum-based fuels, alcohol–biodiesel–diesel hybrid fuel blends can be used in existing engines to achieve both environmental and energy benefits. There are many technical barriers in the direct use of alcohol in diesel engines due to its low cetane number, lower calorific value, lower flash point, poor solubility in diesel fuel and reduced lubricity. Biodiesels act as emulsifiers or surfactants that allow more alcohol in the hybrid fuel blend, improve blend tolerance for water, and keep the blend fuel stable. Blending of biodiesel and ethanol with fossil diesel dramatically improved the solubility of ethanol in diesel fuel over a wide range of temperature [14]. Alcohol–biodiesel–diesel hybrid fuel blends are stable well below the sub-zero temperature and have equal or superior fuel properties to regular diesel fuel [13].

3.4. Biodiesel and its benefits

Biodiesel has the following advantages as an alternative diesel fuel:

- Biodiesel can be blended with diesel fuel in any proportion and it can be used in conventional diesel engine without any major modification.
- Slightly higher viscosity of biodiesel makes it an excellent lubricity additive [15].
- Biodiesel is nontoxic and biodegradable when introduced in neat form [16].
- Since biodiesel is an oxygenated fuel, it contributes to a more complete fuel burn.
- Cetane number of biodiesel is higher than those of vegetable oil and diesel fuel [17] and hence produce less THC emission [18,19].
- No emission of green house gases and low unregulated emission like aldehyde and PAH emissions [17,19–22].
- Since biodiesel can be used in conventional diesel engines, the renewable fuel can directly replace petroleum products; reducing the country's dependence on imported oil.
- Biodiesel offers safety benefits over petroleum diesel because it is much less combustible, with flash point greater than 150 °C, compared to 77 °C for petroleum diesel. It is safe to handle, store, and transport [23].
- Inorganic make up of bio-derived oils may work as an inherent additive for particulate trap regeneration [24].
- Erosion control in the production areas by planting of perennial tree crops.
- Biodiesel does not contain any aromatic components, and with low sulfur content produces low exhaust PM emissions, sulfur dioxide and lower aromatic HC emissions [19,21,22].
- Use of biodiesel results in low carbon build up and low smoke emission [25–27].

3.5. Limitations of biodiesel

The drawbacks of biodiesel in diesel engine operation are:

- Increase in NO_x operation in most cases [23,28–30].
- Slight decrease in fuel economy on energy basis (about 10% for pure biodiesel operation).
- Thickens more than diesel fuel in cold weather, may need to use blends in subfreezing conditions [31].
- Pour points and cloud points are much higher than diesel fuels, which can cause filter plugging and operational difficulties in cold climates [32].

4. Higher NO_x and lower smoke emissions from oxygenated fuels

The oxygenated fuels like biodiesel and alcohols are widely acknowledged as reducing PM emissions but yielding higher NO_x emissions. The NO_x increase may limit the use of oxygenated fuels in non-attainment areas and is therefore a significant barrier to market expansion for these fuels. The effect of oxygenates on NO_x emission depends on engine technology, its operating and maintenance conditions. Recent engine testing studies continue to present NO_x emission results that vary widely and appear to depend on engine manufacturer or engine design. Although higher overall cylinder temperature is an indicator of higher NO_x, it must be stated that the temperature distribution in the cylinder is more important, thus causing in some cases, NO_x to increase and in others to decrease. However, it was reported by most of the researchers that the oxygenated fuels emit higher NO_x emissions which alone is discussed in this paper.

Saptaru and Romig [30] analyzed power parameters including engine speed, torque, brake horse power and fuel flow rate with the soybean methyl ester (SME)—diesel blends and noticed only small variations (less than 1.5%) as the percentage of SME was increased, which is shown in Table 1.

As shown in Table 2, increasing the percentage of SME blended with diesel led to increased emissions of NO_x and CO_2 and reductions in THC and CO.

Sharp et al. [21] tested a heavy-duty diesel engine with 100% soy biodiesel and observed a 10% increase in NO_x, a 77% reduction in PM, and a 25% reduction in CO. Schmacher et al. [33] observed that fueling of CI engines on 100% soybean methyl ester (SME) slightly reduced the power when compared to that fuelled with petroleum diesel fuel. The specific power developed by CI engine fuelled on 100% biodiesel will vary depending on engine design and fuel delivery. CO, HC, PM and smoke exhaust emissions tend to be lower when fuelled on biodiesel while NO_x exhaust emissions tend to be higher. Grimaldi et al. [34] calculated the heat release rate for rapeseed methyl ester (RME) and they observed higher biodiesel combustion rate. They concluded that because of lower heating value of RME than that of diesel by 12%, a higher mass is required to obtain the same energy release. The higher biodiesel burning rate is undoubtedly responsible for its higher NO_x emissions, although, on the other hand, it contributes to the reduction of soot formation.

Table 1
Peak power comparisons (SME/ARB).

Test	ARB diesel	20/80	30/70	40/60
Engine speed, rpm	2003	2003	2003	2002
Engine power, bkW	195	198	196	192
Engine torque, N m	928	946	933	918
Fuel flow, kg/h	47.8	49.4	49.3	49.0

Table 2
Comparison of exhaust emissions from SME/ARB blends (g/(bhp h)).

Fuel blend	Total PM	THC	NO_x	CO	CO_2
100% ARB	0.257	0.57	4.43	1.22	671
20/80	0.270	0.48	4.70	1.12	688
30/70	0.258	0.42	4.78	1.03	688
40/60	0.258	0.38	4.89	0.95	686

Tsolakis et al. [35] studied the engine performance and emissions of a diesel engine operated on diesel–RME blends. The authors observed that the increase of RME percentage in the fuel blend appears to reduce the ignition delay, increase the rate of fuel burnt in the premixed phase and shift the start of combustion to an early stage and hence increase the in-cylinder pressure compared to petroleum diesel combustion. Biodiesel such as RME is less compressible than diesel fuel, so the pressure in the pump-line-nozzle type fuel injection system can develop faster, and pressure waves can propagate faster in biodiesel than diesel even at the same nominal pump timing. As a result, the injection of biodiesel fuel starts earlier with higher pressure and rate and at the same CA degree, the mass of biodiesel injected is higher than the corresponding mass of diesel. The increased RME viscosity leads to reduced fuel losses during the injection process, which leads to a faster evolution of pressure and, thus, advances the injection timing [29]. The combustion of the increased injection pressure and similar cetane number of RME compared to diesel results in an increased amount of fuel undergoing premixed combustion at an early stage. The higher density of RME in conjunction with the increased injection pressure, results in delivery of a higher amount of fuel at the same injection setting conditions. Combustion, therefore, takes place over a shorter period of time, and this possibly allows less time for cooling by heat transfer and dilution, which results in higher NO_x formation associated with the combustion of RME.

Graboski et al. [36] reviewed a range of earlier biodiesel studies, and conducted emissions studies on a Detroit diesel series 60 engine using blend of a 34% aromatic diesel and a methyl soy ester with a cetane number of 56.4 and an oxygen content of 11% by weight. The EPA heavy-duty engine transient test (40 CFR, Part 86 Subpart N) was employed. PM emissions (cold and hot test composite) declined from 0.30 g/(bhp h) on diesel to 0.10 g/(bhp h) on pure biodiesel. However, NO_x emissions rose from 4.64 to 5.17 g/(bhp h).

McCormick and Tennant [37] produced biodiesels from soybean oil, canola oil, yellow grease, and beef tallow and tested them in two heavy-duty engines. The biodiesel fuels were tested neat and as 20% by volume blends with a 15 ppm sulfur petroleum-derived diesel fuel. NO_x and PM results for the tested B20 (20%

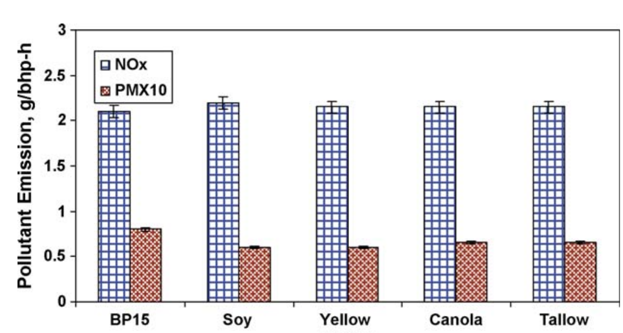

Fig. 1. NO_x and PM emission results for testing of B20 fuels in Cummins ISB engine (error bars = one standard deviation).

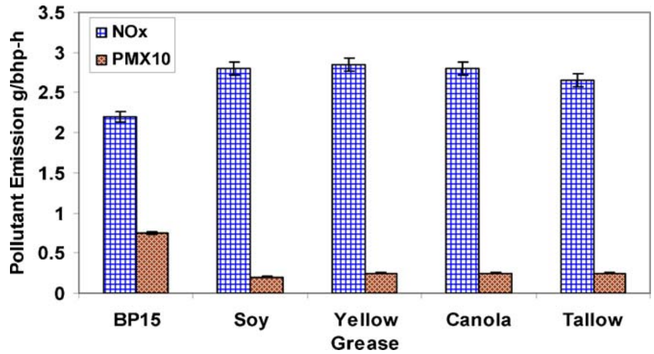

Fig. 2. NO_x and PM emission results for testing of B100 fuels in Cummins ISB engine (error bars = one standard deviation).

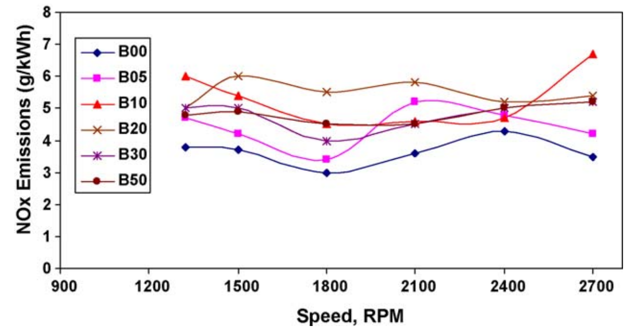

Fig. 4. NO_x emissions for different blends.

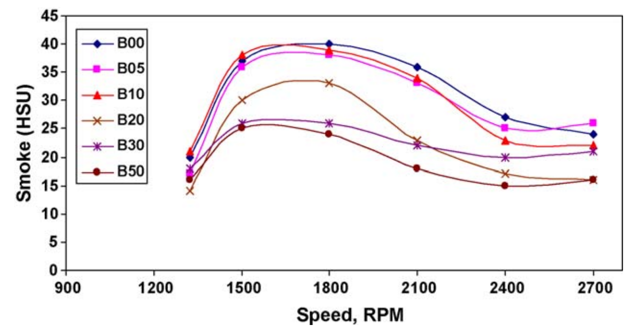

Fig. 5. Smoke number at full load.

biodiesel by volume) and B100 (neat biodiesel) fuels, are shown in Figs. 1 and 2 respectively. Both B20 and B100 produce reductions in PM that is independent of biodiesel feedstock. NO_x emissions increase significantly for B100 and the increase varies with biodiesel feedstock. For B20, the NO_x increase is evident for all biodiesel fuels but the effect of feedstock is much less pronounced.

Choi et al. [29] examined the combustion of diesel/biodiesel blends using a single cylinder Caterpillar 3400 engine with the capability of performing split injections. They, too, observed the substantial reduction in PM and slight increase in NO_x emissions found by other researchers. They also compared emissions from a blend of diesel and octadecene with the biodiesel blend. The octadecene was chosen to resemble the biodiesel but contains no oxygen. The octadecene did not offer the PM reduction benefits of biodiesel, thus suggesting that it is the oxygen content of the fuel that yields desirable emission behavior.

The United States Environmental Protection Agency (EPA) produced a review of published biodiesel emission data for heavy-duty engines [37]. The results for NO_x, PM, CO, and HC are illustrated in Fig. 3. The chart shows that, on an average, substantial reduction in PM, CO, and HC can be obtained through the use of biodiesel. However, there is also an increase in NO_x emissions, by approximately 2% for B20 blends and 10% for B100, an on average. The engine model, year and technology exhibited a large influence on NO_x emissions with the change in NO_x for B20 ranging from roughly +8% to −6%, but averaging +2%.

Sinha and Agarwal [8] carried out a study on a four stroke, four cylinders, transportation DI diesel engine with blends of RME and diesel ranging from 5 to 50% ester in the blend. Higher NO_x emissions were observed by them for all biodiesel blends compared to mineral diesel (B00) as shown in Fig. 4. Smoke opacity of exhaust from different fuels is shown in Fig. 5. It shows that the smoke opacity values for all biodiesel blends are lower than that of mineral diesel and smoke opacity decreases with an increase in biodiesel blend concentrations. This result suggests lower PM emissions from biodiesel-fuelled engines.

The same trend of increased NO_x and decreased smoke emissions were observed by Crookes [38] for RME–diesel blends, which are shown in Figs. 6 and 7 and Agarwal and Das [39] for linseed oil methyl ester in a single cylinder variable speed engine.

McCormic et al. [40] investigated several oxygenates, n-octanol (C8), decanoic acid (C12), methyl soy ester (C17) using a 6V-92TA DEC II engine. They found that all oxygenates tested, produced a significant PM reduction in the range of 12–17% while NO_x emissions increased. Shi et al. [14] studied the use of oxygenates consisting of 20% (v/v) ethanol with methyl soyate (denoted by BE) added in 15% (BE15) and 20% (BE20) with base diesel fuel. Due to the more complete combustion of ethanol, both BE15 and BE20 produced higher NO_x emissions than that of B20 and base diesel fuel.

Chen et al. [41] investigated engine performance and emission characteristics of soy methyl ester–ethanol–diesel blend fuels in Cummins-4B diesel engine. They observed 30% smoke reduction with E10B (ethanol—10%; biodiesel—5%; diesel—85%), 55% with

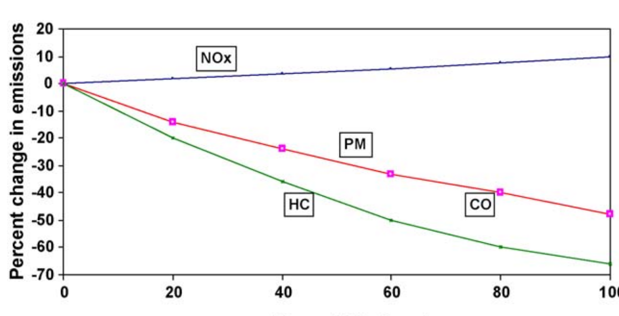

Fig. 3. Summary of United States EPA evaluation of biodiesel impacts on pollutant emissions for heavy-duty engines (note PM and CO curves overlap).

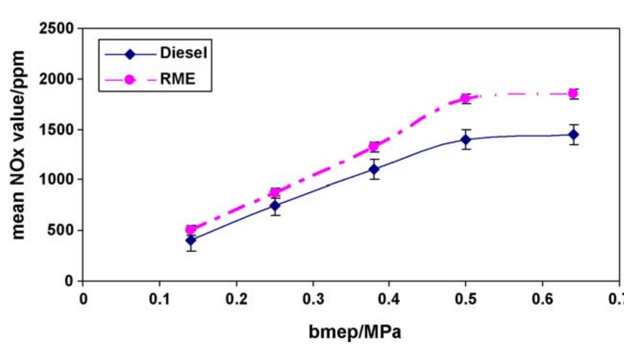

Fig. 6. Comparison of NO_x mole fraction variation with load and fuel type.

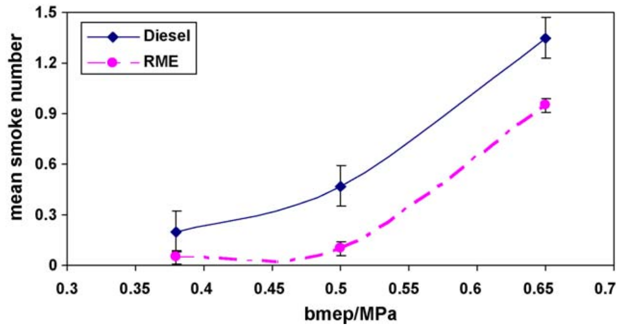

Fig. 7. Comparison of Bosch smoke number variation with load and fuel type.

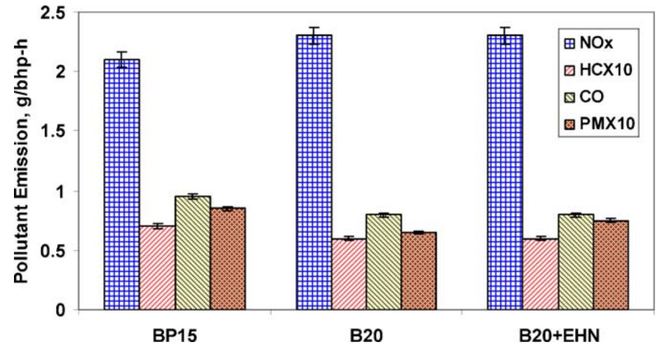

Fig. 8. Results for testing of soy B20 containing 4000 ppm of EHN in the Cummins ISB engine (error bars = one standard deviation).

E20B and 85% with E30B compared to diesel at BMEP of 0.58 MPa. At full load, all the three fuels produced higher NO_x emissions than diesel fuel. They observed that with E10B, the engine produced highest NO_x emissions of 10.7 g/(kW h) as compared to 8.73 g/(kW h) with diesel at full load.

Shi et al. [13] studied the emission characteristics of a tri-compound oxygenated diesel fuel blend (BE–diesel), on a Cummins diesel engine with a blend ratio 5:20:75 (ethanol:methyl soyate:diesel fuel) by volume. The results from the operation of diesel engine with BE–diesel showed a significant reduction of 30% PM emissions and 5.6–11.4% increase in NO_x emissions at tested conditions. The summary of the report given by several researchers is shown Table 3, which further strengthens the need to reduce NO_x emissions from the engines fuelled with oxygenated fuels.

5. NO_x reduction technologies

5.1. Use of additives

NO_x emissions can be reduced in diesel engines by blending of cetane improvers. McCormick and Tennant [37] studied the effect of 2-ethyl hexyl nitrate (EHN) in Cummins ISB engine and DDC Series 60 engine with soybean biodiesel and compared it with diesel containing 15 ppm (BP15). The effects of EHN on emissions are shown in Figs. 8 and 9 for the ISB and Series 60 engines, respectively. The ISB was tested with B20 + 4000 ppm of EHN producing a cetane number increase of 8 units. Series 60 engine was tested with B20 + 5000 ppm of EHN producing a cetane number increase of 10 units. In both cases, addition of EHN had no significant effect on NO_x, confirming the cetane insensitivity of NO_x emissions in engines. The cetane improver had no impact on emissions of other regulated pollutants.

5.2. Retarded fuel injection timing

Retarded injection is an effective method employed in diesel engines for NO_x control. However, this method leads to deterioration in engine power, increased fuel consumption, increased HC and excess smoke [52]. Monyem and Van Gerpen [53] evaluated the impact of oxidized biodiesel on engine performance and emissions in a John Deere 4276T turbocharged DI diesel engine. The effect of retarding the injection on NO_x and smoke emission is shown in Figs. 10 and 11. By retarding the injection by 3° CA, NO_x emissions of oxidized and unoxidized biodiesel reduced considerably, while smoke emissions of all blends increased drastically as shown in Figs. 10 and 11.

5.3. Emulsion with biodiesel and water

Performance tests of a single cylinder DI diesel engine showed that both the NO_x concentration and smoke density reduced without worsening BSFC with water to fuel volume ratios of 15–

Table 3
Studies with various blends of diesel and biodiesel reported with higher NO_x emissions.

Sl. No.	Author	Engine used	Fuel used	Observations
1	Munoz et al. [42]	Isuzu model 166430, IDI, 4-cylinder, TC DE	Sunflower ME	Reduced HC,CO; high NO_x
2	Nagaraja and Prabhu Kumar [43]	Single cylinder, 4-stroke, DI DE	Rice bran oil ME	B20 gives 2.5% higher BTE, less smoke, high NO_x, and HC
3	Kinoshita et al. [44]	Single cylinder, 4-stroke DE	Palm ME, RME	Almost same BTE, HC and NO_x are less for PME, and high for RME
4	Bhardwaj and Abraham [45]	CRDI, 4-stroke, TC intercooled DE	Pungamia ME	Lower CO, UBHC, PM and smoke; slightly higher NO_x
5	Karthikeyan and Mahalakshmi [46]	Single cylinder 4-stroke DE-dual fuel mode	Turpentine oil–diesel	35% high CO, 45% high UBHC; at full load 21% high NO_x
6	Sundaresan et al. [47]	Single cylinder water cooled 4-stroke DE	Jatropha ME	Comparable BTE, less CO, HC and smoke; high NO_x
7	Takayuki and Takaaki [48]	Single cylinder water cooled 4-stroke DI DE; 411 cm^3	Rice bran ME	High BTE, 13% higher NO_x, at full load; lower CO, THC and smoke at all loads
8	Senatore et al. [12]	TC DI 4-stroke DE, 1929 cm^3, 68 kW	RME	Same power, higher NO_x, lower smoke, and CO
9	Canakci [49]	Jhon Deere 4276T 4 cylinder 4-stroke DI medium swirl DE	Soybean ME	11.2% higher NO_x, 0.5% higher CO_2, reduction of 60% smoke, 42.5% HC, 18.4% CO
10	Postrioti et al. [50]	European passenger car engine, 1910 cm^3, 74 kW, TC with intercooler, DI common rail	Soybean ME	High CO and NO_x; low HC and smoke
11	Rakopoulos et al. [51]	Mercedes-Benz, mini bus diesel engine, 6 cylinder TC after cooled	Cotton seed ME, sunflower ME	Same BTE, similar performance, higher BSFC, high HC and NO_x, low CO; cotton seed ME better than sunflower ME
12	Crookes et al. [38]	Ricardo E6 variable CR research engine, 12.78 kW @ 3000 rpm	RME	Lower smoke, higher NO_x, 38% aldehyde and ketone reduction, lowest soot/carbon materials, lowest mutagenic effect

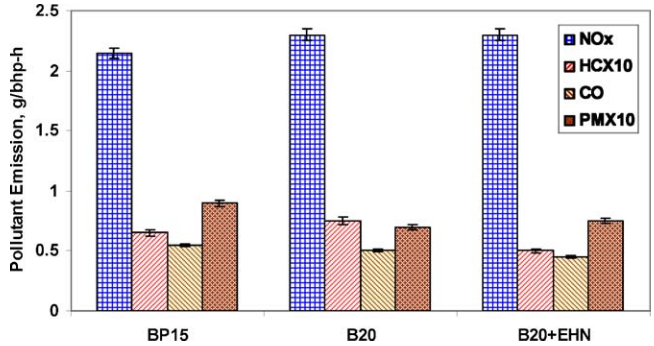

Fig. 9. Results for testing of soy B20 containing 5000 ppm of EHN in the DDC Series 60 engine (error bars = one standard deviation).

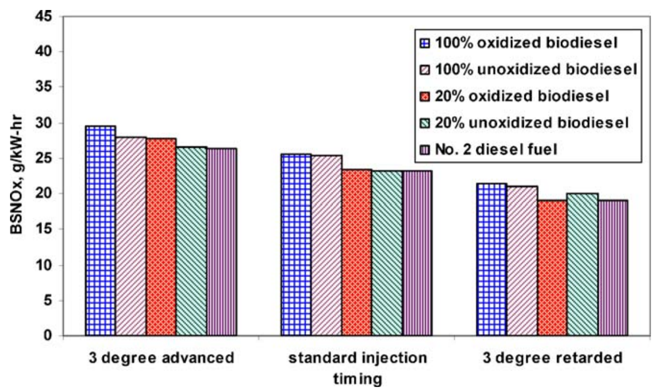

Fig. 10. Brake-specific NO_x emissions at full load.

30% at a rated output [54]. Engine performance with fairly stable emulsions of biodiesel derived from used frying oil and water was examined by Yoshimoto et al. [55]. Emulsified biodiesel with 30% water showed a significant reduction in NO_x (1100–400 ppm) while maintaining the minimum BSFC value achieved with petroleum diesel.

Combustion characteristics of waste vegetable oil methyl ester (WME) was investigated by Hamasaki et al. [56] and obtained better combustion and lower smoke emission. 18% reduction of NO_x was achieved by emulsifying WME with 15% water. To get drastic reductions in NO_x emissions, water emulsified fuels from biodiesel and diesel with varying water addition rates combined with cooled EGR was examined by Yoshimoto and Tamaki [57]. The result obtained by them showed that at a rated output, the emulsified diesel with water to base fuel volume ratio of 30% reduced NO_x from 1020 to 190 ppm with 21% EGR condition maintaining the minimum BSEC value achieved with EGR free

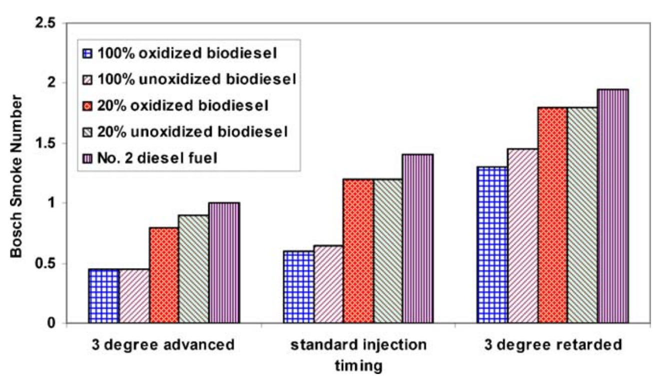

Fig. 11. Bosch smoke number at full load.

diesel operation. However, the smoke density increased by 28%. The combined operation of 21% EGR and emulsified biodiesel with 30% water showed significant reductions in NO_x (to 170 ppm) without worsening smoke emissions, although the BSEC increased by 4%.

Emulsified rapeseed methyl ester with 15 wt% water and without adding any emulsifier was tested in a DI diesel engine by Kinoshita et al. [44]. They recommended that there was no need to use any emulsifier because when crude glycerin was used as an emulsifier, it increased the ignition delay and exhaust emissions. Water emulsification on the other hand leads to corrosion.

5.4. Use of EGR

EGR reduces oxygen concentration and peak combustion temperature, which results in reduced NO_x level. On the other hand, EGR significantly increases smoke emission, fuel consumption and reduces thermal efficiency unless suitably optimized. The use of EGR was more effective (higher NO_x reduction with lower increase in smoke) in the case of B20 combustion compared to diesel [58]. Hot EGR, a low cost technique of exhaust gas recirculation can be effectively used to meet the stringent emission norms. Cooled EGR method even though effective, is expensive and difficult to implement [59]. Kimura [52] has reported serious difficulties in maintaining gas cooler system with respect to its cooling capacity, weight, etc., especially in higher load regions. Practical difficulties faced in a cooled EGR system like corrosion of gas cooler, cooling capacity at higher load, extra weight are avoided with hot EGR.

5.5. EGR in biodiesel-fuelled engine

Recently EGR has emerged as a necessary means to meet the United States Environmental Protection Agency (EPA) NO_x regulations for heavy-duty diesel engines with the implementation of 2004 regulations where NO_x release is restricted to 2.5 g/(bhp h) [60]. Many researchers like, Peng et al. [61], Shi et al. [62], and Miller Jothi et al. [63] studied the effects of EGR in diesel engines whereas researchers like, Tsolakis et al. [64,65] and Rakopoulos et al. [66] studied the effects of EGR in engines fuelled with biodiesel. Pradeep and Sharma [59] used hot EGR for NO_x control in a CI engine fuelled with biodiesel from Jatropha oil. They observed NO emission reduction when the engine was operated under hot EGR levels of 5–25% and they optimized the EGR level as 15% based on adequate reduction in NO emissions, minimum possible smoke, CO, HC emissions and reasonable brake thermal efficiency.

Engine performance and emissions of a diesel engine operated with diesel–rapeseed methyl ester (RME) blends with EGR was investigated by Tsolakis et al. [35]. The use of EGR in the case of biodiesel-fuelled engine resulted in the increase of the ignition delay and shifted the start and end of combustion to later stages in the compression stroke and expansion stroke respectively. The authors observed that the use of 20% EGR was more effective and obtained NO_x reduction of 54% and 50% for B20 and B100 at IMEP of 6.1 bar. The authors concluded that the main reasons for the higher NO_x reduction with the use of EGR in the case of biodiesel fuelling are: (i) the increased CO_2 dilution as more CO_2 enters the combustion as part of the EGR compared to diesel, (ii) the lower relative air/fuel ratio with biodiesel compared to operation with diesel, and (iii) the retardation of the already advanced combustion from the use of biodiesel. The interesting feature of biodiesel is that, as recent exhaust-gas fuel reforming studies have shown, EGR can significantly improve the hydrogen production and reforming process efficiency compared to diesel [64,65].

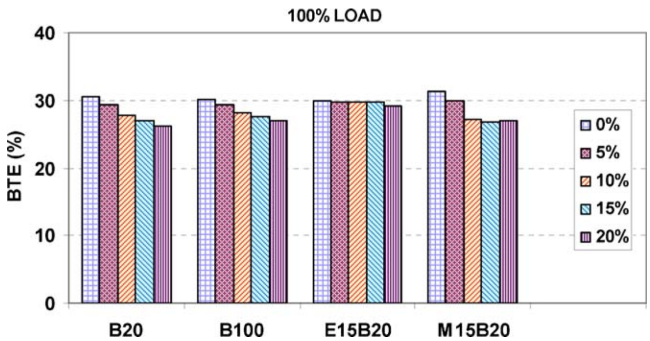

Fig. 12. Effect of EGR rate on brake thermal efficiency for tested fuel.

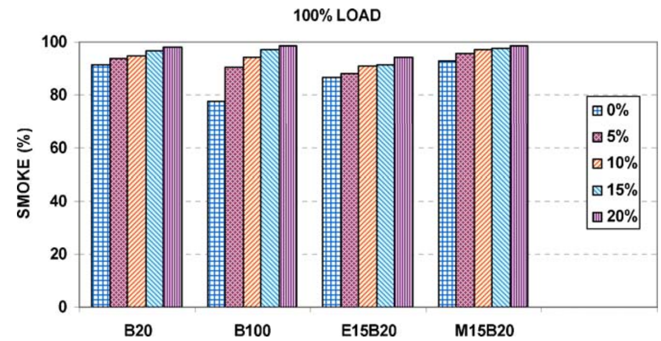

Fig. 15. Effect of EGR rate on smoke emission for tested fuel.

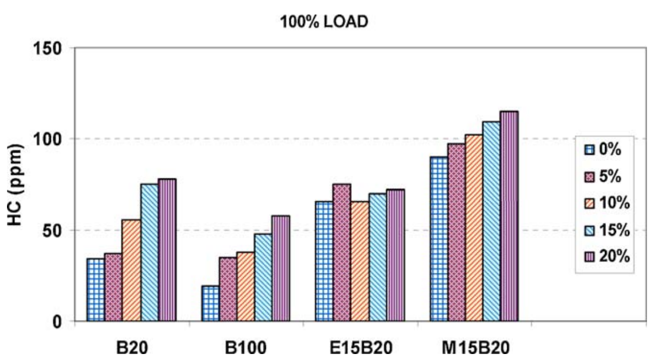

Fig. 13. Effect of EGR rate on HC emission for tested fuel.

6. Performance and emission characteristics of oxygenated fuel blends with EGR

Experiments were conducted at a speed of 1800 rpm and static injection timing of 23° bTDC was used for all tested fuels. The biodiesel used in this study was prepared from jatropha oil by transesterification process. The obtained jatropha methyl ester (B100) was blended with diesel fuel in 20% by volume (B20), with diesel and ethanol (E15B20) in the ratio 15:20:65 (ethanol—15%; biodiesel—20%; diesel—65%) and with diesel and methanol (M15B20) in the same ratio, and used to study the effect of EGR on engine performance and emissions. The cooling water outlet temperature was maintained at 65 °C during all the experiments [67]. The EGR flow was controlled manually by a valve and the EGR level was determined volumetrically as the percentage reduction in volume flow rate of air at a fixed engine operating point. The inlet charge was kept as much as possible at the same temperature while using EGR, so that the effects of the inlet charge temperature on the ignition delay and combustion process could be eliminated.

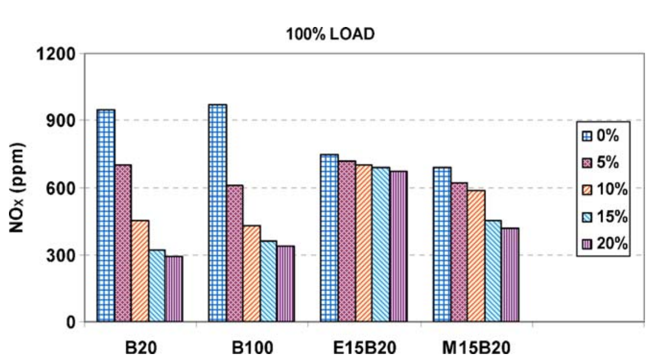

Fig. 14. Effect of EGR rate on NO_x emission for tested fuel.

Fig. 12 shows the influence of EGR rate on brake thermal efficiency (BTE) of the tested fuels. The EGR rate was varied from 5 to 20% and in all fuelling cases, EGR addition resulted in reduced BTE. The use of EGR resulted in increased fuel consumption and hence reduced brake thermal efficiency. The effect of EGR rate on HC emission is depicted In Fig. 13. As the EGR rate was increased, due to the dilution of incoming charge by the exhaust gases, availability of oxygen concentration in the combustion chamber reduced and it resulted in higher HC emission.

Figs. 14 and 15 show the influence of EGR rate on NO_x and smoke emission respectively. With 15% EGR rate 65.9% NO_x reduction and 5.4% increase in smoke was observed for B20 and with 20% EGR rate it was 69% and 6.9% respectively. While for B100, 74% NO_x reduction and 19.4% increase in smoke was observed at 15% EGR rate and at 20% EGR rate it was 75.6% and 20.6% respectively. In the case of tri-compound oxygenated diesel fuel blends, due to the high latent heat of evaporation of ethanol as well as methanol, the combustion temperature was reduced which resulted in lower NO_x emissions compared to biodiesel fuels at 0% EGR itself. Compared to B20 and B100, the NO_x emission reduction obtained for E15B20 and M15B20 are only marginal with the increased EGR rates. Further NO_x reductions in these three-compound oxygenated fuel blends can be obtained by optimizing fuel injection timing and compression ratio.

7. Conclusions

Higher NO_x emissions from various types of diesel engines fuelled with oxygenated fuels reported by many researchers are discussed. Few possible NO_x reduction technologies are compared and reviewed. The main conclusions are:

- Additives are not effective enough to reduce NO_x emissions; they are expensive and produce higher emissions.
- Although retarded injection timing reduces NO_x emissions considerably, this method results in reduced brake thermal efficiency and increased smoke.
- Biodiesel emulsion with water reduces NO_x emissions effectively, but it results in corrosion of engine components.
- EGR is a very effective method to reduce NO_x emissions up to 50–70% in biodiesel-fuelled engines. A low cost reduction technique of hot EGR can be preferred to avoid the drawbacks of cooled EGR.
- Maximum reduction in NO_x emissions with minimum increase in smoke was observed with 15% EGR in B20 fuel operation. EGR is the most effective method to reduce NO_x emissions in the case of B20 compared to B100.

- When EGR used in diesel engine operated with tri-compound fuels, the NO_x emissions reduction observed was only moderate compared to the reduction obtained with biodiesel. Further reduction in NO_x emissions can be made possible in the tri-compound fuels by optimizing the fuel injection timing with EGR.

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